TITLE: High Torque Nozzle Development for the 2.75-Inch Rocket System

HIGH TORQUE NOZZLE DEVELOPMENT FOR THE 2.75-INCH ROCKET SYSTEM

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ABSTRACT

The 2.75 Inch Rocket System is a multi-service system consisting of launchers, warheads, and rocket motors. The air vehicle is a warhead and rocket motor combination that flies a free flight ballistic trajectory to the target. The launch platform consists of both rotary and fixed wing aircraft. The 2.75-inch system is used in large numbers for prosecuting soft and lightly armored targets and additionally provides unique battlefield illumination, target marking, and smoke screening capabilities. The small size of the rocket allows the platform to carry a large number of rockets and the small size of the warhead is appropriate for many targets where low collateral damage is desired.

While the 2.75-Inch Rocket System has been modified over time to improve the performance, the system still experiences problems hitting a point target resulting in a high number of rockets needed to perform a mission. This problem is due to both low precision (wide impact distribution) and low system accuracy. Precision is affected by thrust misalignment, downwash and crosswinds whereas accuracy is affected by the launch system (aircraft and launcher) and the launch environment (air density). Both precision and accuracy need to be improved to increase the ability of the 2.75-Inch Rocket System to hit targets. The Naval Surface Weapons Center, Indian Head (NSWC-IHD) and General Dynamics Armament Systems (GDAS) are jointly developing a high-torque nozzle to improve the rocket precision. The current nozzle produces 3 ft-lb_f of torque. The high-torque nozzle is designed to provide more than 10 ft-lb_f of torque and significantly improves rocket precision by averaging out the thrust misalignment. The nozzle torque will shut-off at rocket exit from the launcher to limit the rocket spin rate below its natural bending frequency. A separate effort will modify the large pop-out fins to reduce the downwash effect from the helicopter. The program is currently in the design phase.

DESIGN BACKGROUND

Erodable vanes and spin tab designs have been investigated for several years for application in ground-to-air and air-to-ground rockets. We began the design effort by reviewing available information pertinent to discrete duration motor torque application. From that review, two design approaches were investigated; a plastic erodable vane installed within the motor nozzle and a metal tabbed vane extending into the plume immediately aft of the nozzle that rotated out of the plume after launcher exit. A literature search was initiated to obtain information related to both design approaches.

Erodable Vane Design – Advanced Rocket System (ARS)

During the early to mid 1990s, the US Navy initiated an Advanced Rocket System project to improve the existing 2.75 inch rocket. Several warhead and motor initiatives were investigated, one of which was an erodable vane design. The ARS program utilized two types of vane design:

1 – The original design (Figure 1) consisted of eight, 0.67 inch long, polycarbonate vanes with an angle of attack of 26°. The erosion rate of these vanes was approximately 0.0033 inch/ms.

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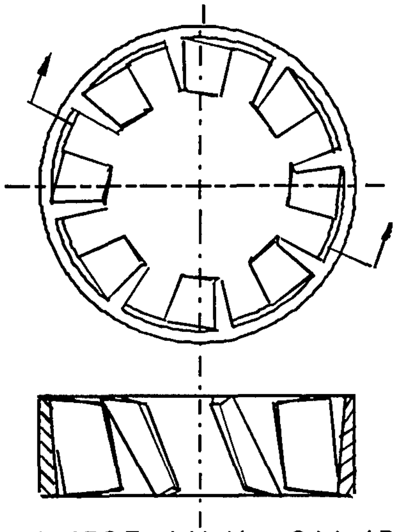


Figure 1. ARS Erodable Vane Original Design

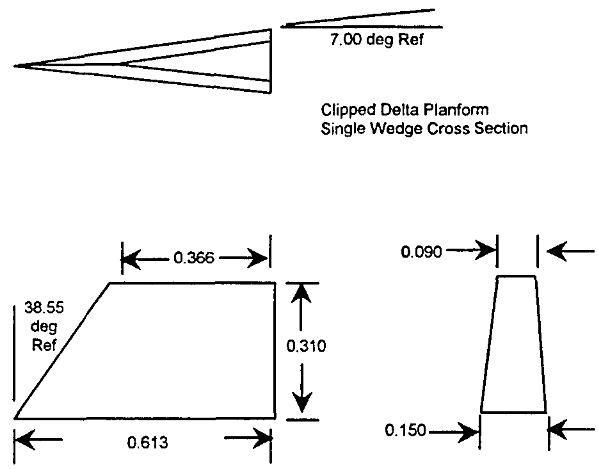


Figure 2. ARS Erodable Vane Modified Design

2 – A modified design (Figure 2) consisted of eight, 0.613 inch long by 0.150 inch thick polycarbonate vanes with a canted leading edge. The angle of attack was 18°. The torque-time curve (Figure 3) indicated a slightly higher leading edge erosion rate of approximately 0.0038 inch/ms.

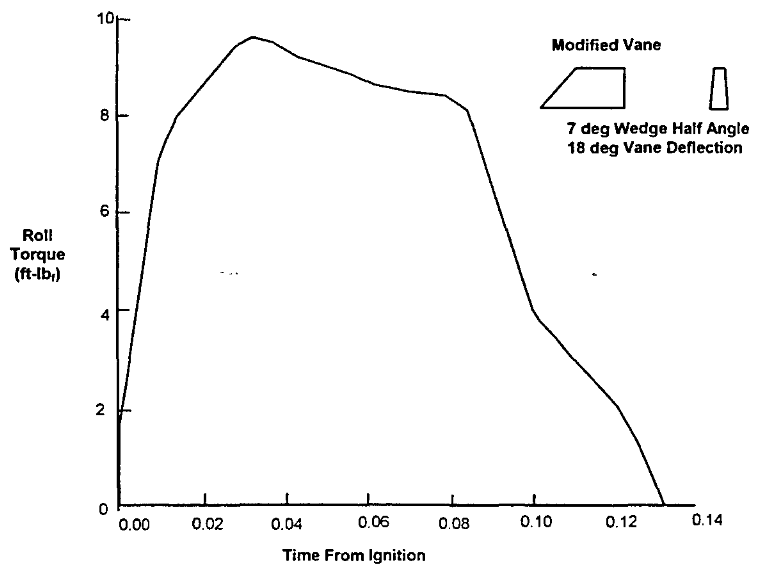


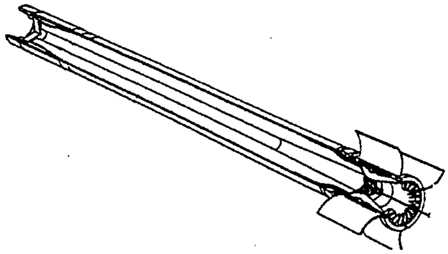
Figure 3 ARS Modified Vane Torque versus Time

The ARS erodable vanes were pressed into the nozzle from the aft end and bonded into place. Assembly difficulties with the erodable vanes were encountered and the project was terminated in 1995.

Erodable Vane Design – Thiokol Design

Thiokol Corporation investigated [1, 2] an erodable vane design in the late 1970s and early 1980s for a TX 783 5.25-inch diameter rocket motor. This program evaluated the erodable spin vane mechanism for achieving rocket spin-up within the launcher. A molded glass epoxy erodable spin vane assembly

comprised of 21 supersonic vane was evaluated. Glass/epoxy was selected to yield the desired vane erosion rate. A schematic of the motor is shown in Figure 4.



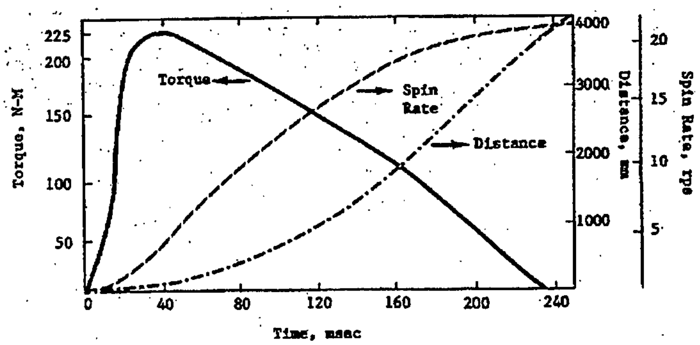


Figure 4 Thiokol's TX783 Spin Vane Schematic

Figure 5 Thiokol's TX783 Spin Performance

Typical spin performance is shown in Figure 5 for a vane span (length) of 0.9 inch. Vane thickness was varied to achieve the required 25 rev/sec spin rate. The propellant used in this program was significantly different from the NOSIH-AA-2 propellant used in the Mk66 motor. The Thiokol propellant was an AP/HTPB/Al composite propellant.

Metal Tab Design – Single Penetrator Kinetic Energy (SPIKE)

In 1977 a technology effort was initiated at the U.S. Army Missile Command, Redstone Arsenal, to investigate small hypervelocity rockets delivering a separating single rod penetrator. The tabs (torque vanes) generated sufficient torque within the launcher to translate to a 40 rev/sec spin rate upon launcher exit. The tabs were attached to spring loaded petals (Figure 6) which deployed at launcher exit, lifting the tabs out of the motor plume.

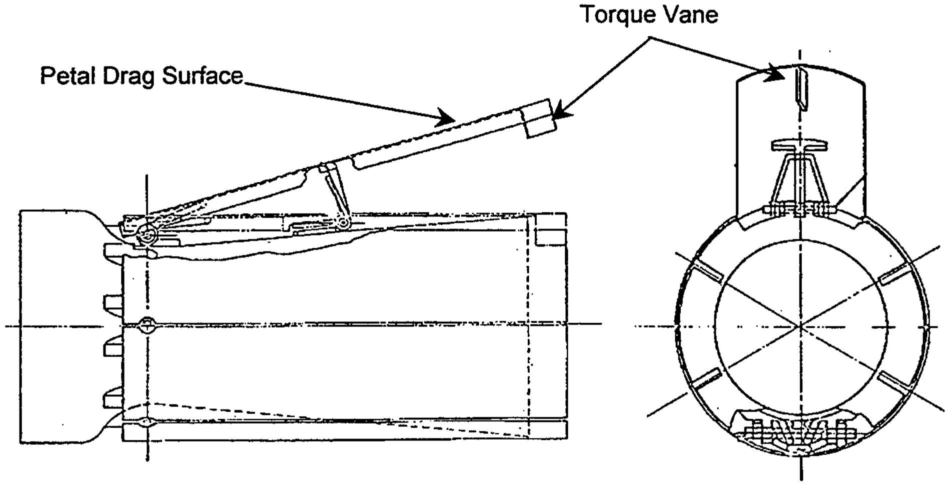


Figure 6 SPIKE Nozzle Configuration

This design approach was not considered a viable candidate due to the number of components, cost and producibility. As a result of this literature search it was decided to further evaluate erodable vanes.

HYDRA-70 VANE DESIGN

A diamond shaped airfoil was initially modeled to exercise a computational fluid dynamics simulation. Two cases were evaluated with the vanes placed at 0° and 20° angle of attack, Figures 7 and 8. Flow pattern around the vanes exhibited the existence of a weak shock wave and number of rarefaction waves. Pressure distribution around the vane was used to compute the rocket spin torque of 34.7 ft-lb$_f$ at a 20° vane angle of attack.

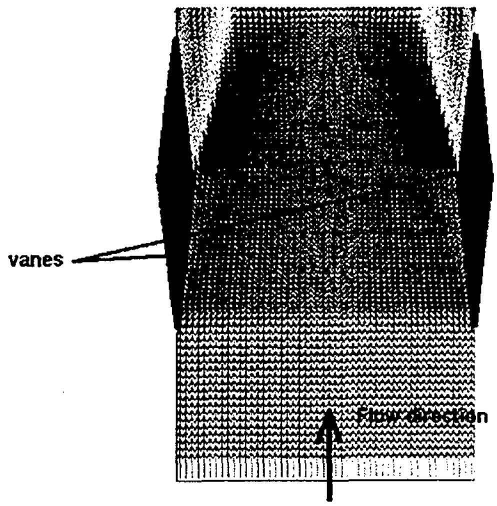


Figure 7 Angle of Attack $\alpha = 0^\circ$

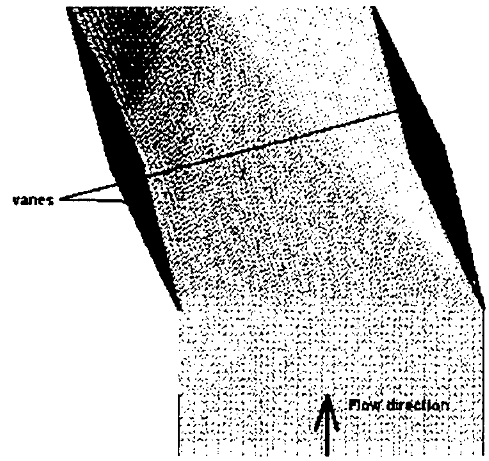


Figure 8 Angle of Attack $\alpha = 20^\circ$

The vane design was modified to accommodate manufacturing and reevaluated with the computational model. Eight wedge-shaped vanes (shown in Figure 9) were placed at a 26° angle of attack. Vane height was fixed at 1.27 cm and located inside the nozzle at an expansion ration of 4.97. Computed initial torque was 32.5 ft-lb$_f$. Reducing the vane height in half reduced the initial torque to approximately 16 ft-lb$_f$.

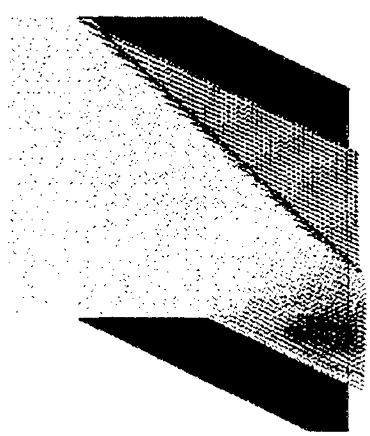


Figure 9 Modified vane design

For this effort, a simplified linear torque decay was assumed such that an initial torque of 20 ft-lbs$_f$ was required to obtain an average 10 ft-lbs$_f$ as shown in Figure 10.

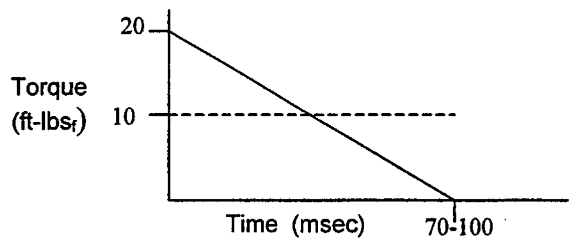


Figure 10. Required Torque versus Time

A final configuration was evaluated using a 16 vane geometry which provided an initial torque of approximately 20 ft-lbs$_f$. The final geometry was based on the structural properties of Nylon 6/6 with 40% glass fill. This configuration was input to the computational model with the results indicating an initial torque of 18.4 ft-lbs$_f$.

The test results of the ARS program were used to validate our computational model. The results indicate that torque generated in ARS firings agreed within 20% of our predictions of pressure load on the vanes (Table 1). The ARS delta pressure was derived from torque data and vane geometry with our computational model predicting 10 bar differential pressure for an 18^o vane configuration.

Table 1 ARS versus MK66 Torque Predictions

	Max. torque	α	Δp	**No. of vanes**	**Vane area**
Mk66	18.4 ft-lb.	26^o	12 bar	16	0.09 in^2
ARS	9.5 ft-lb.	16^o	8 bar	8	0.15 in^2

Erosion Material Investigation

In order to develop a vane for the Hydra-70 rocket motor that would erode in approximately 100 milliseconds, three thermoplastic materials were investigated. These materials were chosen for their melting point, mechanical strength and producibility. Samples of the materials were procured and machined to a common size for static motor firing tests at Indian Head, Maryland.

The samples were subjected to static motor tests to quantify erosion rates under actual exhaust temperature and pressure conditions. Injection molded tensile test specimens of Nylon 6/6, ULTEM and PEEK were installed immediately aft of the exit plane of the motor during motor firing. The mechanical strength of these resins was improved by adding glass fiber reinforcement material. In order to determine the effects of glass fiber fill, two groups of samples were made with each resin. One was filled with 20% volume fraction glass fiber while the second group was filled with 40% volume fraction of glass fiber. The actual test coupons consisted of a 1.25 inch long section cut from each end of tensile specimen "dogbone". The leading edges of the test coupons were radially machined to minimize the airflow disturbance of the coupon. Six coupons of each material were fabricated and measured prior to testing in the rocket exhaust flow.

The coupons were exposed to the rocket motor exhaust on an outdoor test stand at Indian Head, Maryland on October 25 and 26, 1999 with the results provided in Table 2. Due to its high strength and apparent erosion rate Nylon 6/6 with 30% glass fill was recommended for further evaluation.

Table 2. Average Erosion Rate

Material	Avg. erosion rate, in^3/sec	70 msec. vol., in^3	Flexural str., psi
Nylon 20%	0.0739	0.005176	28,500
Nylon 40%	0.0666	0.004663	39,000
ULTEM 20%	0.0635	0.004443	32,500
ULTEM 40%	0.0602	0.004213	37,000
PEEK 20%	0.0631	0.004415	33,000
PEEK 40%	0.0520	0.003641	41,000

Uncertainty with the erosion rates indicated that a second material erosion test should be conducted with the samples placed higher into the exhaust to mitigate the effects of the existing nozzle flutes. Six different configurations were machined from Nylon 6/6 with 30% glass fill and tested at Indian Head. Results of those tests indicated that vane erosion progressed steadily from the leading edge towards the trailing edge as seen in Figures 11 and 12. The incubation period (no visible erosion of leading edge) and the period of linear erosion (leading edge recedes linearly with time) were clearly visible.

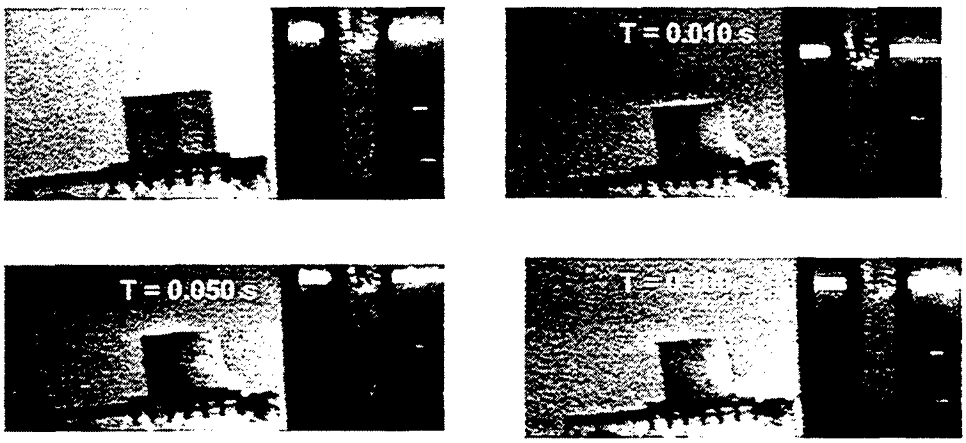


Figure 11 Erosion Test Photographs from High Speed Video

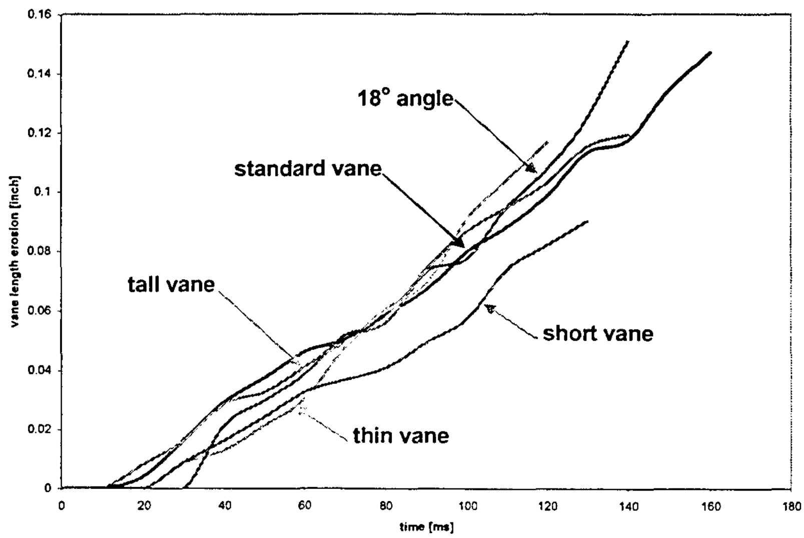


Figure 12 Vane Erosion

During the first 10 – 30 ms no visible erosion of the leading edge was apparent. Review of the ARS and Thiokol data revealed a similar incubation period. Linear erosion rates, obtained after the incubation period, varied with vane configuration and ranged from 0.008 inch/ms to 0.0013 inch/ms. Leading edge erosion rate appeared to be a function of vane thickness and angle of attack and independent of vane height and length.

The vane erosion rates obtained from the historical ARS firings were estimated to be on the order of 0.0035 inch/ms which was three times higher than observed during the vane test. Several possible explanations included: The stagnation temperature of the gases impinging on the vanes are different due to the higher temperature of the ARS propellant (2957°K versus 2378°K for the MK66 motor); The erosion experiment may have failed to replicate conditions within the nozzle therefore, the measured erosion rates are not a predictor of actual erosion rates that would be experienced in the nozzle; The rapid erosion observed (between 90 and 130 ms) in the ARS experiment was due to vane ejections rather than linear erosion of the leading edge.

Based on these findings a motor test was designed to determine actual erosion and torque values. A basic configuration was selected (Figure 13) and fabricated out of 3 different glass filled materials. Nylon 6/6, Delrin and polycarbonate were the materials selected to provide a variation in melting temperature and flexural strength.

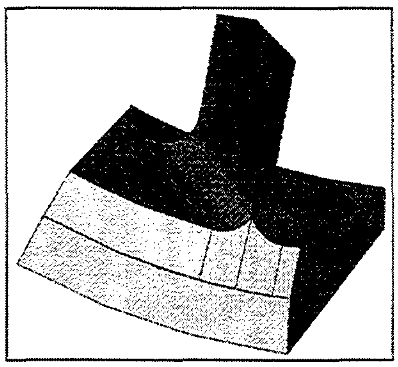


Figure 13 Final Design Configuration

Static Fire Torque Test

MK 66 MOD 5 Rocket Motors modified with prototype high torque nozzles were assembled for the static test. Rocket motor ignition delay, thrust, action time, total impulse and nozzle torque were measured and recorded. In addition to evaluating the higher torque capability of erodable vanes another goal was to determine if the diversion of thrust to torque generation would adversely affect the ballistic and safety performance of the MK66 Rocket Motor.

Test Configuration: The erodable vane ring was bonded between two threaded halves of a steel nozzle body as shown in Figure 14. A test matrix consisting of three commercial epoxy adhesives (3M™ Scotch-Weld™ 2216, ITW Plexus™ MA310, and 3M™ Scotch-Weld™ DP-805) and three plastic materials (Nylon 6/6, Polycarbonate and Delrin) was developed to evaluate assembly and performance characteristics. The erodable torque ring contained 16 vanes with a length of 0.375 inches and a height of 0.25 inches. Vane thickness of 0.063 and 0.125 inches were evaluated. The nozzles were assembled to MK 66 MOD 5 Rocket Motors (Figure 15). The MK 66 Mod 5 Rocket Motor was designed to minimize ejecta thereby reducing the potential of vane impact by ignition wires and connectors.

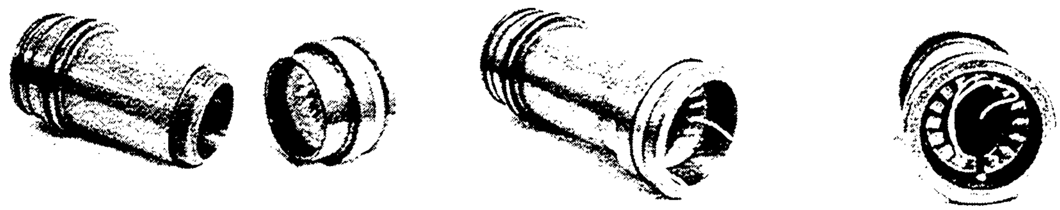


Figure 14. Photographs of a Prototype High Torque Nozzle

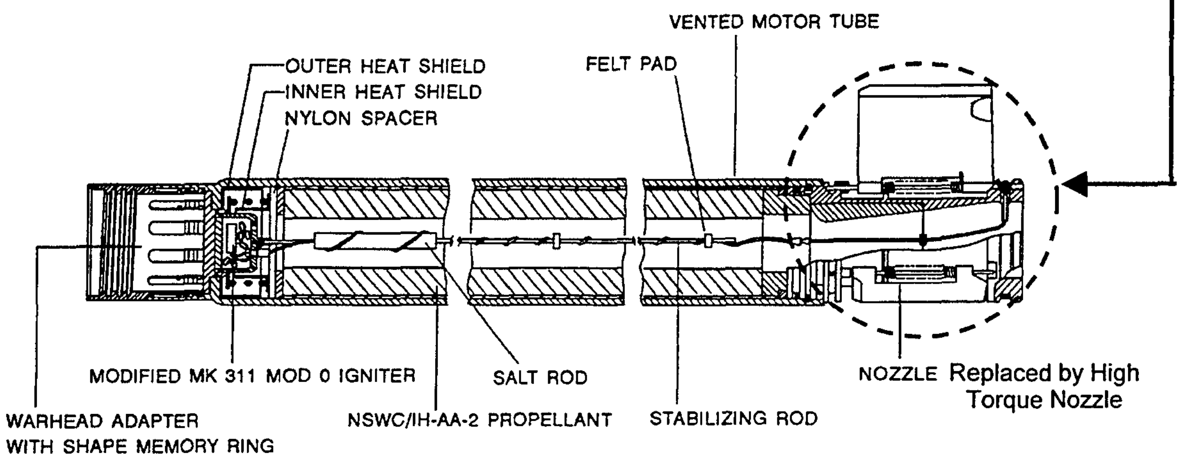


Figure 15. Test Motor Configuration

Test Set-Up: The static fire test was conducted at the Indian Head Division, Naval Surface Warfare Center's Large Motor Test Facility. The test set-up is shown in Figure 16. An aluminum witness board and high-speed camera focused on the nozzle interior were located 20 feet aft of the nozzle.

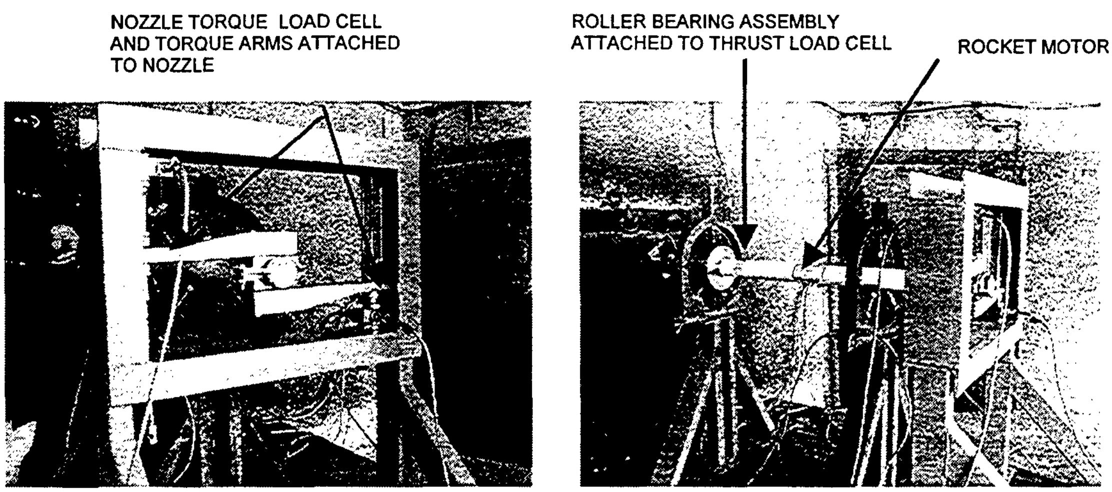


Figure 16. Static Fire Test Set-up

Prior to the rocket motor firings, the motors were divided and temperature conditioned for 8 hours to –50, 77 and 150 °F with the majority conditioned at 77 °F. The motors were fired within 5 minutes after removal from the conditioning chamber. After each motor firing, the witness board was checked for impact damage and the fired motor visually inspected for anomalies such as signs of excessive heating and ruptures.

Motor Performance: Standard 2.75-Inch Rocket Motor ballistic parameters of ignition delay (ms), action time (sec) versus thrust (lbf) and total impulse (lbf-sec) were recorded. The quick look test results were compared against the baseline MK 66 Mod 2 Rocket Motor performance. The high torque nozzles did not appear to adversely affect ballistic performance. Ignition delays and total impulse values were nominal however, one motor fired at 150 °F exceeded the maximum thrust of 2300 lbf in the second half of the motor burn. This high thrust anomaly has been observed in current MK 66 Rocket Motors and is not attributable to the nozzle.

The fired motors were disassembled and visually inspected for anomalies such as hot spots, ruptures and bulges with no anomalies noted. The torque rings remaining in the nozzles were inspected. The 2-piece nozzle body design was successful in retaining the erodable torque ring during the motor burn. The vanes were completely eroded but the erodable torque ring base was intact. The gas flow caused more erosion along the aft edge of the erodable torque ring resulting in the nozzle groove partially exposed as shown in Figure 17. The steel nozzle body groove exhibited minimal evidence of erosion. The aluminum witness board was inspected after each firing. The high torque motor caused only allowable ejecta damage to the board from wires and connectors. Torque vane impact damage to the witness board was insignificant resulting in less than a 0.03-inch dent. (Dents up to 0.3-inches are allowed.)

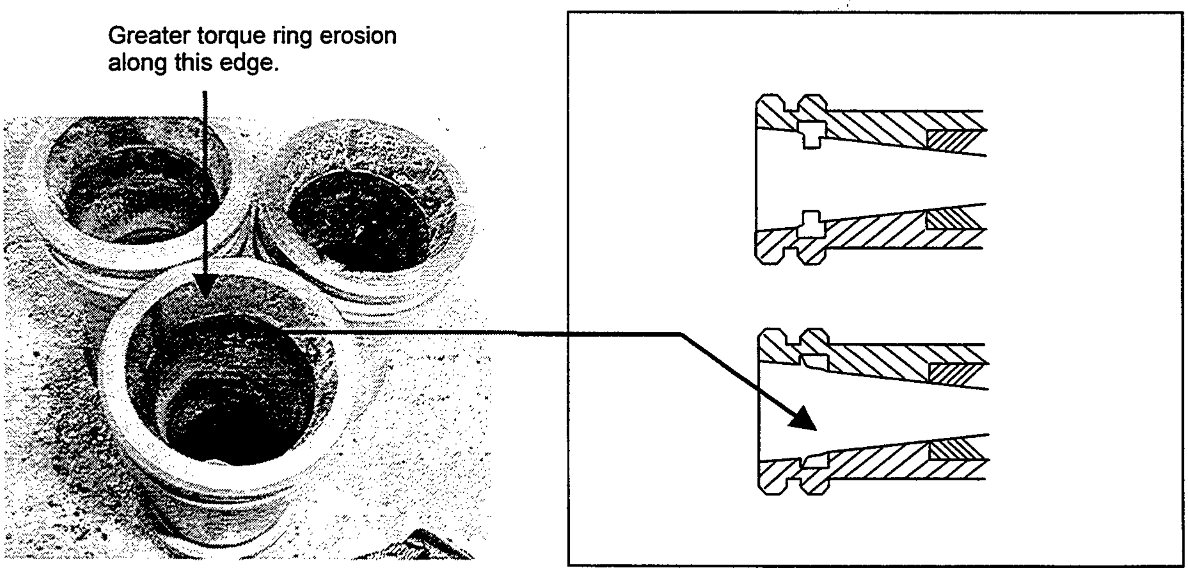


Figure 17. Post-Test Photograph of High Torque Nozzle

Nozzle Torque Performance: The test nozzles provided erosion and torque data required to further refine the design to meet the performance goal of 10 ft-lb_f torque for the first 100-milliseconds of motor burn. Several MK 66 MOD 2 Rocket Motors were static fired at 77 °F to baseline the torque instrumentation. The MK 66 MOD 2 Rocket Motor Nozzle produces approximately 3.2 ft-lb_f torque at 77°F. During the baseline firings it was noted that significant noise was introduced over the torque data requiring post test data processing, which is ongoing. However, it can be seen from the unreduced torque plots a significant increase in torque over a shorter duration with the erodable vane ring (Figures 18 and 19).

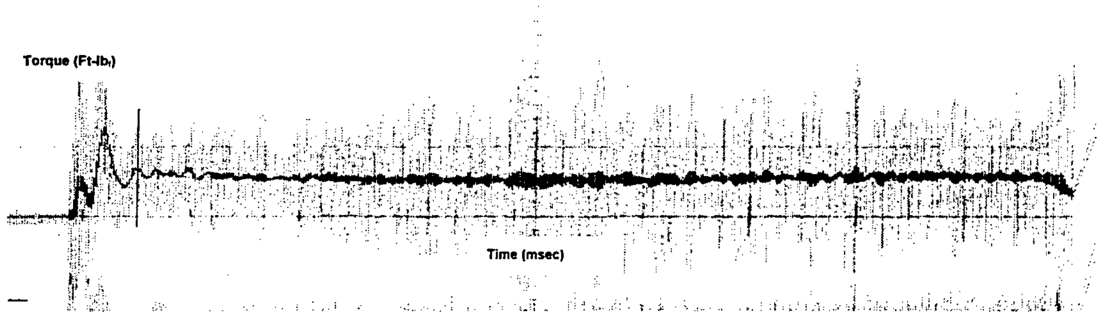


Figure 18. Baseline MK 66 MOD 2 Rocket Motor Nozzle and Torque Profile at 77 °F

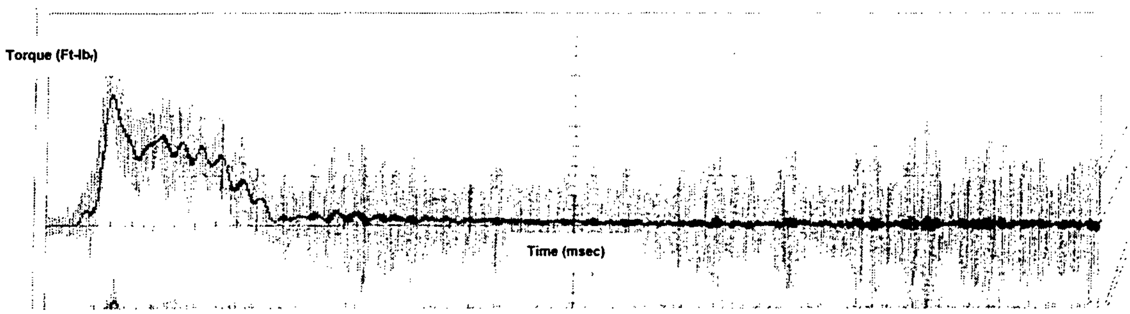


Figure 19. Mk 66 Mod 5 Rocket Motor with Polycabonate Vanes at 77°F (Test Sample 23)

Of the three erodable torque rings evaluated, only the polycarbonate ring demonstrated successful torque generation with a uniform erosion pattern. It appeared in the camera footage that erosion predominates along the leading edge of the vanes with some lesser erosion along the sides. Torque generation lasted approximately 220 milliseconds at 77 °F and 150 milliseconds at 150 °F. The torque sloped down to zero value indicating a progressive erosion pattern. After 130 msec the vanes eroded to the point where the differential pressure began snapping off individual rings. A sequence of still images from the high-speed digital camera captured the erosion of the polycarbonate ring (Figure 20).

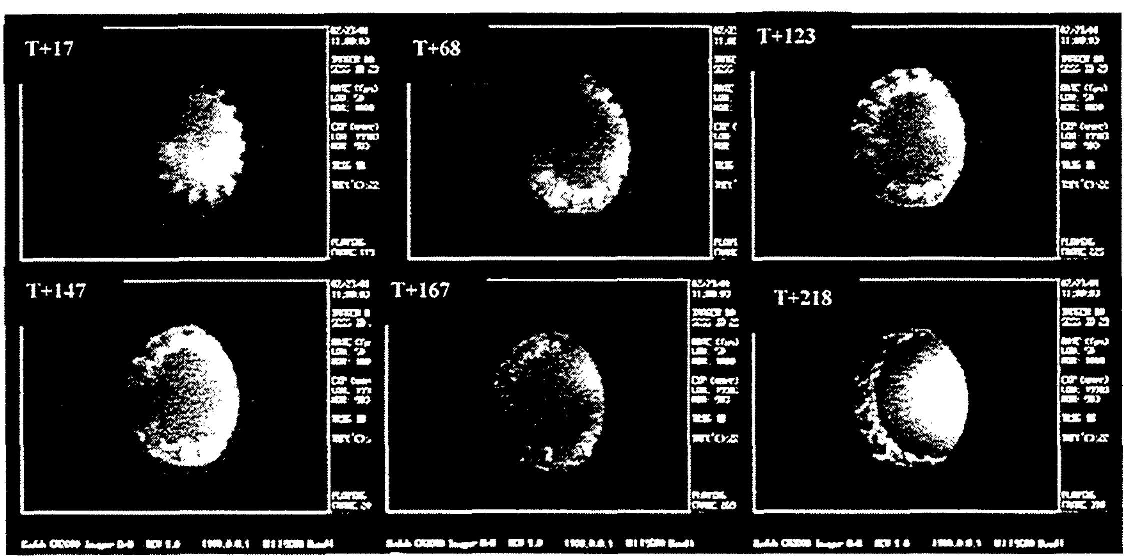


Figure 20. Polycarbonate High Torque Nozzle Erosion Sequence Photographs

The erodable rings made from Nylon 6/6 and Delrin failed to provide lasting torque due to vane breakage or failure of the epoxy adhesive bond at 80 to 120 milliseconds after motor ignition. Nylon 6/6 and Delrin

plastics have weaker structural properties than polycarbonate. The high-speed digital camera captured the vane breakage. There was no indication of motor ejecta causing the vane breakage. It appeared in the camera footage that the leading edge of the vanes erodes at a greater rate than the sides. The cross-sectional shape of all the vanes are rectangular, which contributed to a weaker vane structure as the vane length and cross-section are thinned by the motor gas flow. Future torque vanes will likely have a tapered cross-sectional shape to reduce the possibility of vane breakage.

The araldite 2216 epoxy adhesive was successful in securing the erodable torque rings, however the MA-310 and DP 805 adhesives repeatedly failed after motor ignition. This caused the erodable torque ring to spin rapidly within the nozzle groove. The vanes completely eroded during the motor burn while the base rings were left intact.

SUMMARY AND CONCLUSIONS

This high torque nozzle study conducted by NSWC-IHD and GDAS demonstrated the potential for shorter duration increased torque generation from an eroding torque ring. In addition, the greater division of thrust for torque and the new nozzle configuration did not adversely affect the motor's ballistic or safety performance. Further data reduction and analysis will be performed to refine the nozzle and vane ring performance. Additional ground and ballistic tests are planned within the next year.

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